HIGH POWER/WEIGHT RATIO BRAKING DEVICE BASED ON SHAPE MEMORY MATERIAL TECHNOLOGY

[0001] The invention relates to brakes.

[0002] When it comes to slowing down or completely stopping the rotation of a mechanical system, different braking strategies are being used. The most common brake technologies include viscous brakes, hydrodynamic brakes where a fluid is forced to pass through a flow restriction orifice, magnetorheological brakes where a particular fluid changes its viscosity under the application of a variable magnetic field, electromagnetic brakes where a force opposing the rotation of a system is set up by inducing eddy currents within a metal disc inserted between two electromagnets, and friction brakes where two surfaces are pressed one against the other.

[0003] The are many types of friction brakes, which are set apart by the shape of their friction surfaces and the nature of their activation principle. There are six main types of friction brakes, namely drum brakes, disc brakes, belt brakes, electromechanical and electromechanical power off brakes and magnetic particles brakes. Drum brakes consists of a cylindrical braking surface on to which one or more brake shoes are pressed when the brakes are activated. Friction of the shoe on the drum surface slows down the rotation of the system. Disc brakes use a clamping action to produce friction between a disc and two pads mounted in a caliper. As the caliper pinches the disc with the pads, which are positioned on opposite sides of the disc, the rotation of the system is slowed down. Belt brakes consist of a friction belt wrapped around a drum. The tension in the belt is proportional to the gripping force between the belt and drum, thus increasing this tension slows down the rotation of the drum. All these friction brakes may either be hydraulically, pneumatically or electrically activated as long as the selected

activation principle ensures adequate functioning of the mobile brake element (shoe, pads or belt).

[0004] Electromechanical brakes operate via an electric actuation, but transmit torque mechanically. When voltage is applied to the brake, a coil is energized creating a magnetic field, which turns the coil into an electromagnet. The resulting magnetic flux attracts an armature that is brought into contact with friction pads. Since the armature is fixed relative to the shaft and the pads are fixed relative to the frame, activation of the brake slows down the rotation of the system. In most designs, springs hold the armature away from the brake surface when power is released. Conversely, in some designs, a series of springs force the armature in contact with the brake surface when no power is applied to it. These brakes, called electromechanical power off brakes, are released by applying voltage to a coil, which pushes the armature away from the brake surface.

[0005] In magnetic particle brakes, magnetic particles are located in a cavity where they simply lay when no power is applied. However, as soon as voltage is applied to a coil located on top of the cavity, the magnetic flux created tends to bind the particles together. As the voltage is increased, binding of the particles becomes stronger. Since the brake rotor passes through these bounded particles, the resistance force created on the rotor slows down the rotation of the system.

[0006] In the field of prosthetics, several types of brakes have been used in the past to control relative pivotal movement between components of the prosthesis, each having their benefits and drawbacks.

[0007] Viscous brakes are well suited for prosthetic applications but are subject to leakage and failure under high loading conditions. Moreover, their relatively high weight makes them less interesting compared to other solutions.

[0008] Magnetorheological fluids are theoretically suitable for applications where the viscosity of the braking device needs to be rapidly and accurately modified. However, practical applications have shown that this change in viscosity is not rapid and accurate enough to achieve acceptable performances in the field of prosthetics. Moreover, as with the viscous brakes, their relatively high weight is detrimental to their selection in applications where dynamic braking is not a requirement.

[0009] Friction brakes are not recommended for dynamic braking applications since the friction coefficient of the contact surfaces tends to change after extended use. However, their simplicity, compactness and lightness make them an interesting choice whenever dynamic braking is not necessary.

[0010] Furthermore, all braking devices presented above have a common limitation in that they require power to remain activated or inactivated.

[0011] Accordingly, it is an object of the present application to obviate or mitigate some or all of the above disadvantages.

SUMMARY

[0012] According to one aspect of the present invention, there is provided a friction brake assembly to act between a pair of relatively moveable components and comprising a braked member connected to one of said components, a carrier connected to the other of said components and a friction pad attached to the carrier for engagement with the brake member. A first actuator is operable upon the carrier to move the friction pad into engagement with the brake member. A second actuator is operable upon the carrier to move the friction pad away from the brake member. A control operates selectively on the first and second actuators.

[0013] According to a further aspect of the present invention, there is provided a prosthesis having a pair of limbs pivotally connected on one another by a mechanical joint. An actuator is connected between the limbs to effect relative rotation there between and a brake acts to inhibit such relative motion. The brake is operative upon the actuator to inhibit further movement in the joint.

[0014] The braking device exhibits the ability to maintain a given state of activation when no power is supplied to it. The preferred embodiment of this device takes advantage of some particular characteristic of shape memory alloys (SMA), namely the shape memory effect. The preferred embodiment of brake may be packaged on a leg prosthesis for above knee amputees but is not restricted to this specific application. It suits any general application where a braking action needs to be applied between a pair of components.

[0015] In the preferred embodiment, actuation of the brake is provided a set of shape memory alloy (SMA) wires positioned, in an agonistic-antagonistic configuration on each side of a brake lever. Braking and releasing phases are dictated by the austenitic transformation of the SMA wires by the application of an electrical current to shorten one set of wires. During brake activation, shrinking of the braking wires brings the friction pad in contact with a rotating drum creating a braking friction torque. Once the brake has been activated, deformation of a flexible component prevents the releasing of the brake by maintaining sufficient normal force between the drum and the friction pad. Conversely, upon activation of the releasing wires, the pad looses its grip and the drum is free to rotate.

[0016] Half of the SMA wires are used for brake activation while the other half is used for brake release. Braking amplification factor is determined by the position of the lever pivot. Aluminum 6061-T6 is well suited as a bulk material for weight reduction purposes. In order to increase the brake coefficient of friction, aluminum-bronze and steel are used for braking pad and drum manufacturing

respectively. It is estimated that a 5V – 50A power supply is suitable for brake activation and release according to the SMA specifications.

[0017] Other features and advantages of the present invention will be more readily apparent from the following detailed description, which proceeds with reference to the accompanying figures.

[0018] Figure 1 is a perspective view of a prosthesis incorporating a braking system.

[0019] Figure 2 is a perspective view on an enlarged scale of the braking system utilized in Figure 1.

[0020] Figure 3 is a further perspective view of the assembled components of the braking system shown in Figure 2.

[0021] Figure 4 is an exploded view of the components of the braking system shown in Figure 1.

[0022] Figure 5 is a free body diagram of the brake in an activated state.

[0023] Figure 6 is a deformation analysis of a component utilized in the brake shown in Figure 2.

[0024] Figure 7 is a trigometric analysis of a brake pad displacement for the brake shown in Figure 2.

[0025] Figure 8 is a free body diagram of the components shown in Figure 6, and

[0026] Figure 9 is a free body diagram similar to Figure 8 in a different mode of operation.

[0027] The braking system has been developed in the context of a prosthesis for an above knee amputee and therefore will be described within that context to illustrate the particular attributes of the system to this field of endeavor. However, it will be understood that the braking system is more generally applicable.

[0028] Referring therefore to Figure 1, a powered prosthesis 10 has a knee joint assembly 12 connected between a lower limb 14 and a socket 18. The knee joint assembly 12 permits relative rotation between the socket 18 and the lower limb 14 which in turn is connected to a foot 15 through a cantilevered support beam 20. Rotation of the knee joint 12 is controlled by an actuator 16 pivotally connected, as indicated at 22, to the lower limb assembly 14 and at its opposite end to bifurcated arms 24 forming part of the knee joint assembly 12. The actuator 16 is a screw type actuator with an armature rotatable within the outer casing and engaged through a screw thread with a linearly displaceable output shaft 26. Rotation of the armature induces longitudinal displacement of the shaft 26 causing the actuator 16 to lengthen or shorten and cause a corresponding rotation in the knee joint assembly 12. Further details of the actuator and knee joint assembly may be found from the Applicants corresponding PCT Application PCT/ and accordingly further description is not required at this time. In order to inhibit rotation of the knee joint assembly 12, a brake assembly 28 is incorporated on the actuator 16, and is operable to inhibit changes in the length of the actuator 16 when engaged. The details of the brake assembly 28 are more readily seen in Figures 2, 3 and 4.

[0029] Referring therefore to Figure 2, the actuator 16 has an outer housing 29 with an end cap 30. An armature is rotatably mounted within the housing 29 and is rotatably supported in the end cap 30 on a boss 32 that projects through the end cap 30. The actuator shaft 26 extends through the boss 32 and is displaceable longitudinally upon rotation of the armature by virtue of the screw

threaded connection between the armature and the shaft 26. Rotation of the shaft 26 is inhibited by its connection to the ears 24.

[0030] The boss 32 has a brake drum 40 secured to it for rotation with the boss 32. A brake shoe carrier 42 is pivotally connected through a pin 44 to a mounting block 46 that projects from the body 29 of actuator 16. The carrier 42 acts as a lever and is formed as a semi-cylindrical cup having outer flanges 48 between which is secured a part cylindrical brake shoe 50. The brake shoe 50 is configured to conform to the outer surface of the brake drum 40 and frictionally engage the brake drum.

[0031] The opposite end of the carrier 42 to the pin 44 is connected to a beam 52 that projects radially between a pair of ears 54. The beam 52 is made from electronically non-conductive material and is designed to provide a controlled flexure upon application of a braking force as will be described below.

[0032] The ears 54 are secured to the body 28 of the actuator 16 and project axially to the extent of the brake assembly 28. Each of the ears 54 has an axial slot 56 to accommodate a set of shape memory alloy (SMA) rods 58. The rods are secured to a mounting block 60 which is pivotally secured by a trunnion 62 to the ears 54. The opposite ends of the rods 58 are received in respective sets of holes 64 formed in the beam 52. The rods 58 are secured to the beam 52 through terminal blocks 66, 68 which permits adjustment of the rods to ensure correct positioning of the shoe 50 relative to the drum 40.

[0033] The rods 58 are formed from a shape memory alloy, such as that available under the trademark Nitinol. The rods 58 are pre-stressed and shape memory alloy has the characteristic that a current applied to the rods 58 induces an austenitic transformation causing a shortening of the rods 58. Upon removal of

the current, the length of the rods 58 remains unchanged until a further current is applied.

[0034] The rods 58 are secured to the mounting block 60 through terminal blocks 70, 72 in a manner similar to the terminal blocks 66, 68. The terminal block 70 engages a single rod 58 and has a conductor 74 connected to it. The terminal block 72 is connected to a pair of rods 58 and thus electrically connects the two rods to one another. The arrangement of blocks 70, 72 at both the ears 54 and the terminal blocks 66, 68 on beam 52 is such as to serially connect the rods 58 of each set in an electrical circuit and thereby ensure the same current is applied to each. The conductors 74 are connected to appropriate control circuit responsive to a control signal to apply or release the brake assembly 28.

[0035] In operation, the rods 58 are adjusted such that the carrier 42 maintains the shoe 50 in slight rubbing contact or minimal clearance with the drum 50 with no current supplied to the rods. In this condition, the actuator 16 is operable to rotate the armature and cause longitudinal displacement of the shaft 26 to effect rotation about the knee joint assembly. Rotation of the armature is controlled through suitable control functions as described in the above mentioned published PCT application.

[0036] When braking is required, rotation of the armature is inhibited to maintain the rod 26 in a fixed position by supplying a current through the conductor 74 to one of the sets of rods 58. The rods 58 of that set shorten upon application, upon passage of the current and thereby act through beam 52 to cause pivotal movement of the carrier 42 about the pin 44. This brings the shoe 50 into engagement with the outer surface of the drum 40 and applies a retarding force on the drum. The current supplied through the conductor 74 is terminated and the rods 58 maintain substantially their decreased length to hold the shoe in contact with the drum.

[0037] The application of force from the rods 58 through the beam 52 causes a flexure of the beam in proportion to the load applied. Upon removal of the current to the conductors 74, the deflection in the beam 52 is used as a bias to load the shoe 50 against the drum 40 through the intermediary of the carrier 42 and thereby maintain the braking force at the required level.

[0038] In order to release the brake, current is directed to the other set of rods 58 causing them to shorten and release the load on the carrier 42. Thus, by selectively applying the current to one or other of the set of rods, braking and release can be effected and the brake maintained in a stable position without the continued application of electrical power. During actuation, either to brake or release a current is supplied to one set of rods 58 but not the other. The force generated by the set to which current is supplied is much greater than that necessary to extend the other set over the limited range of motion required, ensuring effect actuation of the brake assembly 28.

[0039] In general, the brake assembly 28 may be adapted to any application where a braking torque needs to be either applied to or released from a mechanical system in rotation, even when no power is supplied to it. The brake requires power input only to change its state from activated to inactivated and vice-versa. The brake operation has been described by way of a particular embodiment describing an example application in which the brake assembly provides emergency braking on a motorized prosthesis in case of power failure and power shut down. The embodiment achieves this by taking advantage of some particular characteristic of shape memory alloys (SMA), namely the shape memory effect. A typical set of criteria to be fulfilled in this example application requires the brake to:

[0040] 1. Be active at power failure or shut down, i.e. the brake remains in position after activation or release even if no power is supplied to it.

[0041] 2. Withstand static load of the amputee when standing on one leg, i.e. the brake produces a minimal torque of 2.2Nm when activated.

[0042] 3. Completely blocks the prosthesis as quickly as possible, i.e. the brake blocks the prosthesis in less than 100ms and may be released in less than 2s.

[0043] 4. Be electrically activated, i.e. the brake may be adapted to a commercially available power supply.

[0044] 5. Respects specific security constraints, i.e. the brake operates in a temperature range defined between –20°C and 40°C, the temperature of the SMA elements never exceeding 150°C and brake lifespan is 100 000 cycles or better.

[0045] 6. Respects specific mass and volume constraints, i.e. the brake, excluding the power supply, not weighing over 500g and not exceeding the approximate volume of a 60mm-diameter and 60mm-long cylinder.

[0046] Using the general arrangement described above, the components may be dimensioned to meet these requirements in the context of a prosthesis. Suitable scaling may be applied to other environments.

[0047] **BRAKING DRUM**

[0048] Drum rotational inertia is a major concern since it affects the dynamics of the prosthesis. In order to keep this parameter as low as possible, the boss 32 maximal diameter is fixed to 23mm and the recommended material is aluminum 6061-T6. In order to improve the coefficient of friction between the boss 32 and the friction pad 50, a 1mm-thick steel brake drum 40 is press-fitted onto the boss 32.

[0049] **FRICTION PAD**

[0050] In order to get high friction coefficient and high heat dissipation properties, aluminum-bronze is preferably used as raw material for the friction pad 50. Static coefficient of friction between aluminum-bronze and steel is estimated to 0.3. Considering this value and the short-shoe friction brake illustrated in FIG. 5 and defined by Equation 1, the normal force between the braking drum 32 and friction pad 50 needs to provide a 2.2Nm braking torque on a 25mm diameter drum is estimated to 587N.

$$N = \frac{T}{\mu r} \qquad \text{Equation 1}$$

[0051] **BRAKE LEVER**

[0052] The brake amplification factor is directly related to the position of the lever pivot point. Considering the recommended stress applied to Nitinol© wires in martensitic state (20MPa), the cross-sectional area A of those wires ($0.78mm^2$) and the normal force estimated above (587N), the amplification factor of the brake is evaluated to $X = 12.5$.

[0053] Equation 2, Equation 3 and Equation 4 are obtained from FIG. 5. Substituting Equation 2 and Equation 3 in Equation 4 and solving for *a*, the position of the pivot point is estimated to *a* = 13mm and *b* = 11mm.

$$X = \frac{(c^2 + d^2)^{1/2}}{b - \mu(a + r)} \qquad \text{Equation 2}$$

$$L^2 = c^2 + d^2 \qquad \text{Equation 3}$$

$$R^2 = a^2 + b^2 \qquad \text{Equation 4}$$

[0054] For weight reduction purposes, aluminum 6061-T6 is recommended as the bulk material for the manufacturing of the carrier 42.

[0055] BEAM

[0056] The beam 52 is made of a material which has a low Young's modulus/Tensile strength ratio, for example fiberglass such as S-Glass-Epoxy. From FIG. 6 and Equation 5 and considering the properties of this material (E = 45GPa and S_u = 1000MPa), a recommended flexural stress σ_{max} = 300MPa, a maximal force at the extremity of the beam 52 $F = N/X$ = 46.9N and a 10mm-long and 10mm-wide beam 52, the minimal beam thickness is estimated to h_{min} = 1mm. From FIG. 6 and Equation 6 and considering the same parameters, the deflection of the beam extremity is estimated to Δ_{DD1} = 0.42mm.

$$h_{\min} = \sqrt{\frac{6FW}{b\sigma_{\max}}} \quad \text{Equation 5}$$

$$\Delta_{DD_1} = \frac{4FW^3}{Ebh^3} \quad \text{Equation 6}$$

[0057] SMA ELEMENTS

[0058] The length of the SMA elements (12, 21) may be obtained from Equation 7, where the active strain of the braking SMA elements (21) is ε_a = 4%, the elastic recovery strain of the releasing SMA elements (12), under the application of a force F = 46.9N, is ε_{rec} = 0.07% while the strain of the braking SMA elements 58 under the same force is ε = 0.5%. Obtaining the displacement of brake carrier 42 extremity DD' from FIG. 7 and the deflection of the beam 52 extremity from Equation 6, the length of the SMA elements 58 is evaluated to be L_{SMA} = 30mm.

$$\varepsilon_a L_{SMA} = DD' + \varepsilon_{rec} L_{SMA} + \Delta_{DD1} + \varepsilon L_{SMA} \quad \text{Equation 7}$$

[0059] Considering Equation 8, the volume of each SMA elements 58 is estimated to be $V = 23.4mm^3$ ($0.78mm^2 \times 30mm$), that is the total volume of the three braking SMA elements 58 as well as the three releasing SMA elements 58 is $V_{TOT} = 70.2mm^3$ ($3 \times 23.4mm^3$). From Equation 9 and considering the density of Nitinol©, $\rho = 6450kg/m^3$, the mass of each SMA elements 58 is estimated to be $m = 1.51 \times 10^{-4}kg$, that is the total mass of the three braking SMA elements 58 as well as the three releasing SMA elements 58 is $m_{TOT} = 4.53 \times 10^{-4}kg$ ($3 \times 1.51 \times 10^{-4}kg$). Finally, from Equation 10 and considering the electrical resistivity of Nitinol©, $\rho_{el} = 0.8\mu\Omega m$ and the three parallel SMA elements 58 on each side of the beam 52 connected in series via steel blocks 66, 68, 70, 72. The electrical resistance of SMA elements 58 is estimated to be $R_{el} = 0.092\Omega$.

$$V = AL \qquad \text{Equation 8}$$

$$m = \rho V \qquad \text{Equation 9}$$

$$R_{el} = \rho_{el} \frac{3L}{A} \qquad \text{Equation 10}$$

[0060] Stress generated by the braking SMA elements 58 during brake activation is obtained from FIG. 8 and Equation 11. Considering $F = 15.6N$, $W = 10mm$, $x = 6mm$, $A = 0.78mm^2$ and $\sigma_m = 100MPa$, this parameter is estimated to be $\sigma_g = 80MPa$. From Equation 12 and considering room temperature, $T_{amb} = 25°C$, Nitinol© transformation temperature, $A_s = 70°C$, Nitinol© stress gradient $d\sigma/dT = 5MPa/°C$ and the value of σ_g estimated above, total temperature elevation for brake activation is estimated to $\Delta T = 61°C$.

$$\sigma_g = \frac{FW + \sigma_m Ax}{AW} \qquad \text{Equation 11}$$

$$\Delta T = \frac{1}{\sigma_g}\frac{d\sigma}{dT} + (A_s - T_{amb})$$ Equation 12

[0061] In a similar way, stress generated by the releasing SMA elements (12) during brake release is obtained from FIG. 9 and Equation 13. In this case, σ_g is estimated to 167MPa and the associated total SMA temperature elevation is estimated to ΔT = 78°C.

$$\sigma_g = \frac{\sigma_m x}{W}$$ Equation 13

[0062] The energy required for brake activation or release is obtained from Equation 14. Considering the latent heat and transformation enthalpy of Nitinol©, c_p = 322J/kg°C and h_T = 24200J/kg, the mass of material, m = 4.53x10^{-4}kg and the temperature elevation values stated above, the energy associated with brake activation is, U_{act} = 19.9J, whereas the energy associated with brake release is, U_{rel} = 22.3J.

$$U = m(c_p \Delta T + h_T)$$ Equation 14

[0063] From Equation 15, considering the parameters evaluated above and the SMA brake functional requirements, the current required to activate the brake in less than 100ms is estimated to I_{act} = 46.5A whereas the current required to release the brake in less than 2s is estimated to I_{rel} = 11A. From Equation 16 and considering the current values evaluated above, the voltage associated with brake activation is estimated to V_{act} = 4.3V whereas the voltage associated with brake release is estimated to V_{rel} = 1V.

$$I = \sqrt{\frac{U}{Rt}}$$ Equation 15

$$V = RI \qquad \text{Equation 16}$$

[0064] **FRAME**

[0065] Components that remain fixed relative to the prosthesis, are considered part of the frame. Those components are: the SMA inserts 60, the trunnion blocks 62 and the lever pivot shaft 44. The SMA inserts 60 are made of, for example, HST II phenolic, a relatively rigid electrical insulator. The trunnion blocks are made, for example, of steel and are used to adjust the initial tension in the SMA elements 58. The lever pivot shaft 44 is made of, for example, steel and is positioned in such a way that the amplification factor of the brake is fixed to X = 12.5.

[0066] Although the present invention has been described by way of a particular embodiment thereof, it should be noted that modifications may be applied to the present particular embodiment without departing from the scope of the present invention.